Interferometry for rotating sources

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Abstract

The two particle interferometry method to determine the size of the emitting source after a heavy ion collision is extended. Following the extension of the method to spherical expansion dynamics, here we extend the method to rotating systems. It is shown that rotation of a cylindrically symmetric system leads to modifications, which can be perceived as spatial asymmetry by the "azimuthal HBT" method.

We study an exact rotating and expanding solution of the fluid dynamical model of heavy ion reactions. We consider a source that is azimuthally symmetric in space around the axis of rotation, and discuss the features of the resulting two particle correlation function. This shows the azimuthal asymmetry arising from the rotation. We show that this asymmetry leads to results similar to those given by spatially asymmetric sources.

Keywords: Hanbury Brown and Twiss method, Rotation, Peripheral collisions
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1. Introduction

Two particle interferometry was adapted to heavy ion physics around 1980, and turned out to be a sensitive tool of determining the space-time extent of the source of the emission in heavy ion collisions. It was a significant early discovery that pion interferometry of exploding sources modifies the determination of the radius of the source [1]. This made the analysis a valuable tool for studying the dynamic expansion of nuclear sources.

Heavy ion collisions with finite impact parameters create systems where we have a large net angular momentum in the initial state, which leads to a rotating [2] and expanding fireball. If the formed Quark-Gluon Plasma (QGP) has low viscosity [3], one can expect new phenomena like rotation or turbulence, which shows up in form of a starting Kelvin-Helmholtz instability (KHI) [4]. Rotation in heavy ion collision recently has been considered, and here we study a new class of exact hydrodynamic solutions for three dimensional, rotating and expanding cylindrically symmetric fireball [5–7].

The created system in relativistic heavy-ion collisions is microscopic and short-lived so only the momentum spectrum of the emitted particles can be measured directly. However, the space-time structure of the collision region can be studied using Hanbury-Brown-Twiss interferometry [8]. This technique uses two particle correlations [1], to probe the space-time shape of the particle emission zone. The size and shape of reaction zone become thus accessible, with the "azimuthal HBT" method [9–15].

The Differential Hanbury Brown and Twiss (DHBT) method has been introduced earlier in [8]. Previously the method has been applied to high resolution Particle in Cell Relativistic (PICR) fluid dynamical model [16] results, and it was shown that rotation can be detected by this modified method. The same PICR model was also used to calculate the vorticity of the flow, and due to the equipartition between the spin and orbit rotation the polarization of emitted particles was evaluated [17], and turned out to be significant. This early prediction was verified recently [18], by the experimental study of Λ and $\bar{\Lambda}$ polarization in Au+Au reactions in the energy range of $\sqrt{s_{NN}} = 7.7 - 39$ GeV/nucl. Furthermore the Λ and $\bar{\Lambda}$ polarizations pointed in the same direction that verified the mechanical, equipartition origin of the polarization in contrast to electromagnetic origin, which would have led to opposite polarizations for Λ and $\bar{\Lambda}$.

In this work we calculate two pion correlation function for a rotating and expanding QGP, formed in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV/nucl, and impact parameter b = 0.7 b_{max}, by using the exact hydro model [5, 6] we determine the effect of rotation on the correlation function (CF) for detectors at different positions. Finally we fit results by "azimuthal HBT" to extract the apparent size of the rotating system in different directions.

2. Correlation Function

We use a simple Exact Model [5] for expanding and rotating systems to demonstrate the sensitivity of the two

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particle correlation method to diagnose rotation. Both polarization [19] and the two particle correlation [20] were already evaluated for this model, with parametrizations adapted for peripheral heavy ion collisions [6].

We consider an azimuthally symmetric system around the rotation axis, y, with Gaussian density profiles with characteristic radii, R and Y and constant temperature T. The initial parameters are given in Table 1, and the initial temperature is taken to be $T = 200$ MeV.

The source function, $S(x, k)$, giving the emission rate in the phase space, x, k, should be integrated over all points, x, of the emitting source to obtain the correlation function:

$$\int d^4x S(x,k) \propto \int w_s \gamma_s \left(k_0 + \boldsymbol{k}\cdot\boldsymbol{v_s}\right) \times \\ \exp\left[-\frac{\gamma_s}{T_s}(k_0 - \boldsymbol{k}\cdot\boldsymbol{v_s})\right] e^{-s_\rho/2} e^{-s_y/2} \frac{ds_y ds_\rho d\varphi}{\sqrt{(s_y)}} \ . \tag{1}$$

Here the spatial integral is performed in cylindrical coordinates, s_y, s_ρ, φ, where s_y, and s_ρ are scaling variables, $s_y = y^2/Y^2$ and $s_\rho = (x^2 + z^2)/R^2$.

The correlation function was evaluated the same way as in Ref. [20]. We should see that the source function explicitly depends on the velocity field, $\boldsymbol{v_s}$, which includes both the expansion and the rotation of the system.

As the rotation axis is the y-axis, the $[x, z]$ plane is the reaction plane. Due to the azimuthal symmetry the radius of the system in the $[x, z]$ plane is R.

According to the conventions of two particle correlation functions in heavy ion physics, the z-axis is the beam axis and determines the LONG direction. In the transverse plane, the x-axis (the direction of impact parameter) is transverse to the beam direction. In this way the OUT direction is the x-direction. The remaining y-axis determines the SIDE direction. Due to the azimuthal symmetry of our specific model the results for the LONG and OUT directions should be identical.

The velocity field in x, y, z coordinates is given by

$$\boldsymbol{v}_s = \Big(\dot{R}\sqrt{s_\rho}\ \sin(\varphi) + R\omega\sqrt{s_\rho}\ \cos(\varphi), \\ \dot{Y}\sqrt{s_y}, \dot{R}\sqrt{s_\rho}\ \cos(\varphi) - R\omega\sqrt{s_\rho}\ \sin(\varphi)\Big) \ , \tag{2}$$

where ω is the angular velocity, and φ is the angle of rotation.

The mean transverse radius is $R = \sqrt{XZ}$, and we use this value when the exact model is studied.

In the practical calculations we use a detectors placed at $\boldsymbol{k}^+ = (k_x, k_y, k_z)k = (0.924, 0, 0.383)k$, $\boldsymbol{k} = (1, 0, 0)k$ and $\boldsymbol{k}^- = (0.924, 0, -0.383)k$, which are orthogonal to the rotation axis, $\boldsymbol{y}$.

3. Results

We calculate the CF for different values of the angular velocity, ω, to see how it is affected. The CFs are shown in Figs. 1 and 2.

t	Y	$\dot{Y}$	ω	R	$\dot{R}$	φ
(fm/c)	(fm)	(c)	(c/fm)	(fm)	(c)	(Rad)
0.	4.000	0.300	0.150	2.500	0.250	0.000
3.	5.258	0.503	0.059	3.970	0.646	0.307
8.	8.049	0.591	0.016	7.629	0.779	0.467

Table 1: Time dependence of characteristic parameters of the fluid dynamical calculation presented in Ref. [6]. R is the average transverse radius, Y is the longitudinal length of the participant system, φ is the angle of the rotation of the interior region of the system, around the y-axis, measured from the horizontal, beam, z-direction in the reaction, $[x, z]$, plane, $\dot{R}$ and $\dot{Y}$ are the speeds of expansion in transverse and longitudinal directions, and ω is the angular velocity of the internal region of the matter.

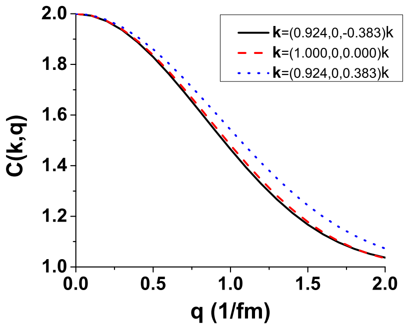

Figure 1: (color online) Correlation Function, $C(k, q)$, for the exact hydro model for the $q = q_{OUT}$ direction. R = 2.50 fm, $\dot{R}$ = 0.25 c, Y = 4.00 fm, $\dot{Y}$ = 0.30 fm, ω = 0.30 c/fm, at t = 0.0 fm/c with k = 5 fm^{-1}. The solid black line is for measuring the correlation function at $\boldsymbol{k}^- = (0.924, 0, -0.383)k$, the dashed red line is for $\boldsymbol{k} = (1, 0, 0)k$ and the dotted blue line is for $\boldsymbol{k}^+ = (0.924, 0, 0.383)k$.

Subsequently the correlation functions is fitted by the azimuthal HBT method and parametrization:

$$C(q,k) = 1 + exp\left(-\sum_{i,j=L,O,S} q_i q_j R_{ij}^2(k)\right) , \tag{3}$$

The obtained radius parameters in the directions L and O are identical due to the symmetry of the model, thus $R_{OO} = R_{LL}$. We took different k-values.

We can compare the different radius parameters, R^2_{ij}, obtained by fitting the results of the CF obtained from the rotating and azimuthally symmetric system, to the "azimuthal HBT" parametrization of eq. (3). The obtained values, $R \equiv R_{OO} = R_{LL}$, are shown in Fig. 3.

The CF increases for larger values of ω which corresponds to a decrease in the measured radius. The approximate radius decrease for $\omega = 0$ to 0.15 c/fm and $\omega = 0$ to 0.30 c/fm is 3-4% and 15% respectively.

In Fig. 3 we can see how the measured radius depends on the rotation velocity ω at time $t = 0$ fm/c.. For a later times we would see a similar effect. Even though ω becomes smaller for later times, the expansion velocity and size of the system are both influencing the CF together

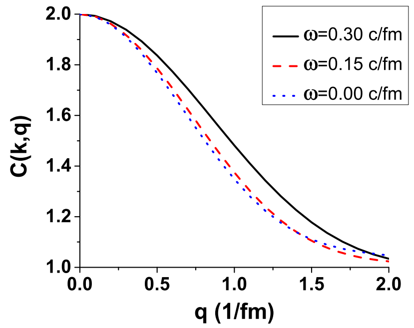

Figure 2: (color online) Correlation Function, $C(k, q)$, for the exact hydro model, for the $q = q_{OUT}$ direction. $R = 2.50$ fm, $\dot{R} = 0.25$ c, $Y = 4.00$ fm, $\dot{Y} = 0.30$ fm at t = 0.0 fm/c with k = 5 fm^{-1}. The solid black line is for $\omega = 0.30$ c/fm, the dashed red line is for $\omega = 0.15$ c/fm and the dotted blue line is for $\omega = 0.00$ c/fm.

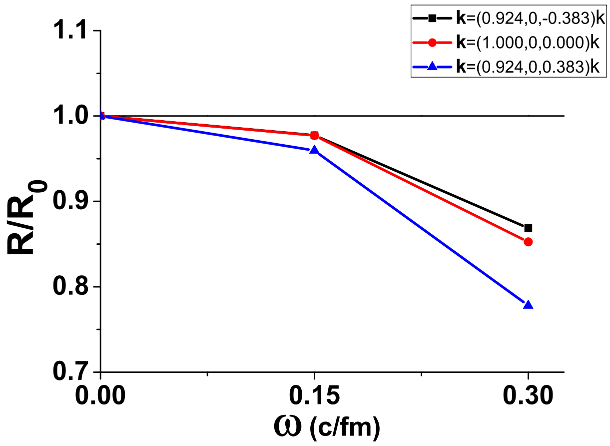

Figure 3: (color online) Ratio of radius from the fit for the correlation function in Fig. 1 and 2 for different directions as a function of ω, the black line is for $\boldsymbol{k}^- = (0.924, 0, -0.383)k$, the red line is for $\boldsymbol{k} = (1, 0, 0)k$ and the blue line is for $\boldsymbol{k}^+ = (0.924, 0, 0.383)k$. R_0 is the observed radius of the system without rotation.

with the rotation. On the other hand there is no effect on the radius parameters if either the rotation or expansion is zero [20].

A higher rotation velocity will decrease the measured size of the system, it also decreases more rapidly for larger values of ω as can be seen from the slope going from $\omega = 0$ to 0.15 c/fm and $\omega = 0.15$ to 0.30 c/fm in Fig. 3. Asymmetry in the size is present if measured at different directions if the system is rotating. If the rotation were reversed the correlation function will also change, where the black and blue lines in Figs. 1 and 3 are exchanged.

The detector at $k^+ = (0.924, 0, 0.383)k$ shows a smaller measured radius for the exact hydro model while the radius showed at $k^- = (0.924, 0, -0.383)k$ is larger. This is also dependent on expansion velocity, temperature and size of the system. The axial size, Y, is not affected by the rotation.

Thus the model results show that rotation significantly influences the HBT evaluation similarly like the expansion, which influences data significantly, e.g. in publications [21–25].

4. Conclusion

Different values of the angular velocity will change the measured "azimuthal HBT" size parameters of the system. It will also create smaller and larger values for the correlation function when measuring at different directions. That the cylindrically symmetric system is rotating will be observed as an asymmetric object in "azimuthal HBT" analysis.

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